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From Reality to Virtual Reality: Comparing Motion Patterns of Masons in Real and Simulated Environments

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Abstract

The construction industry plays a significant role in Canada's economy but faces challenges associated with health and safety, particularly ergonomic hazards involved in manual materials handling. These hazards, such as frequent heavy lifting, often lead to musculoskeletal disorders (MSDs), with masonry and plastering among the highest-ranking occupations for MSD claims. Recent technological advancements have made Virtual Reality (VR) applications increasingly adopted in construction training, demonstrating improvements in engagement, skill development, and safety, offering potential benefits over conventional in-person training. However, its effectiveness in teaching proper ergonomic posture and reducing injury risks has not been thoroughly explored. A key question is whether users adopt different movements when handling a weightless block in a virtual masonry environment. This study conducted experiments to compare real lifts (lifting physical blocks in a real-world setting) and VR lifts (lifting virtual weightless blocks in a VR-simulated environment), assessing motion behaviour in both contexts. In both experiments, while performing the same tasks of lifting blocks, participants were asked to wear a motion capture suit to record the motion data. The collected data were processed for analysis using the Rapid Upper Limb Assessment (a standard test for ergonomic risk), followed by a detailed analysis of the scores for body sections, including upper arm, lower arm, neck, and trunk. Experimental results demonstrate a significant statistical difference in motion behaviour between VR and real-life tasks, particularly in the trunk and neck. We conclude that VR training developments for the trades must recognize this limitation.

Keywords

motion capture, virtual reality, ergonomics, masonry

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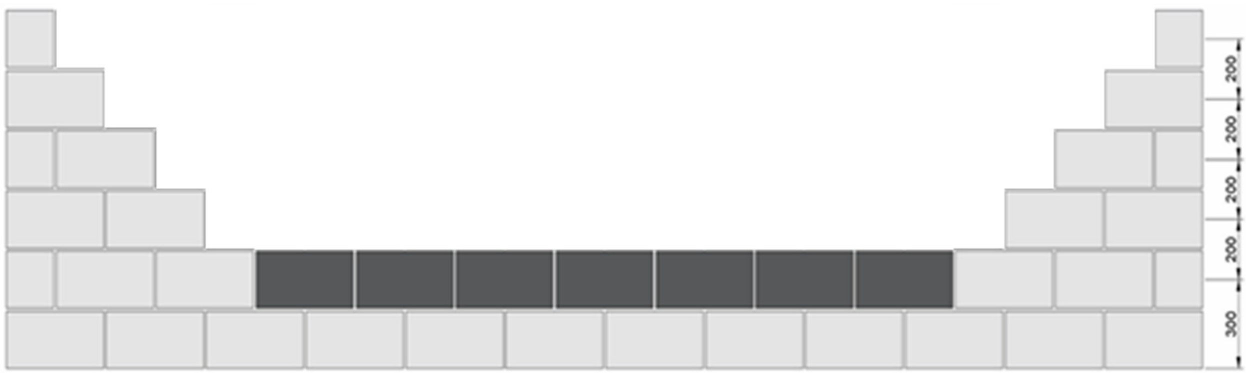
Introduction
The construction industry is a key driver of economic growth in Canada, employing over 1.6 million people. It creates job opportunities, bolsters supply chains, and stimulates investments [1]. Over the past decade, the industry has consistently contributed approximately $150 billion annually to the national economy [2]. Despite its significant economic contributions, the construction industry faces notable occupational health challenges, with ergonomic hazards being a key concern for worker health and safety. Manual materials handling, such as frequent and heavy lifting, which are everyday tasks in construction, increases workers' exposure to these hazards, often resulting in MSDs [3].

The Infrastructure Health & Safety Association reported that, among various construction trades, masonry and plastering are ranked among the top five occupations with the highest number of MSD claims from 2021 to 2023 [4-7]. These injuries not only affect workers' health but also impose substantial economic challenges on society. Notably, MSDs place a significant financial burden on the healthcare system. For example, a prior study discovered that the total cost of MSD-related care for adults in Ontario amounted to $1.6 billion during the 2013–2014 fiscal year [8].

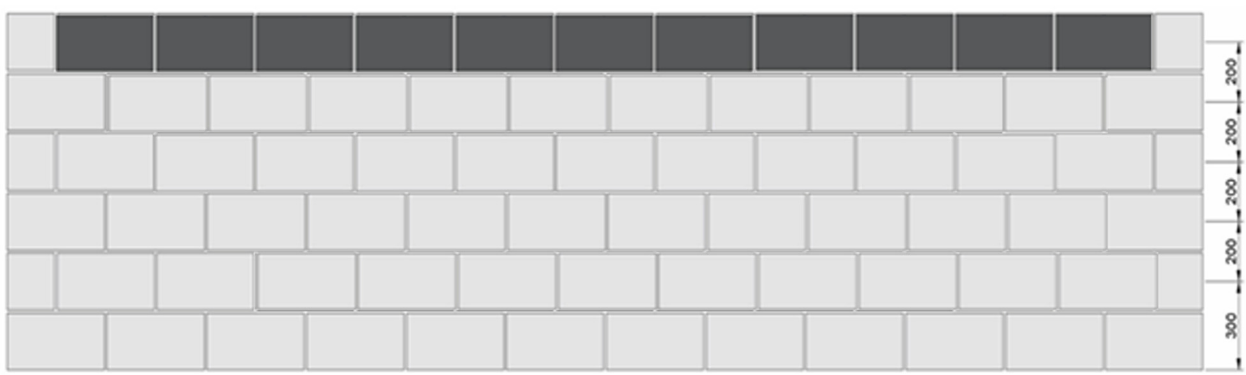
Despite efforts to reduce MSD risks in construction through traditional training methods, recent advancements in technology have led to adopting VR applications in construction training. Previous research has shown that VR training is more effective than conventional in-person training, offering increased engagement, enhanced skill development, and reduced costs and risks, particularly in improving construction safety [9-12]. However, the adoption of VR for ergonomics training in construction, specifically in masonry work, has not been adequately explored due to its limitation in simulating the physical weight included in real-life tasks. This study began by posing the question of whether training with simulated, weightless masonry blocks in a virtual masonry environment can effectively achieve the desired outcomes for masonry training. To address this question, the study investigated the validity of using VR for ergonomics training, particularly in masonry work, by comparing human motion behaviour during block lifting in real and VR environments. The Rapid Upper Limb Assessment (RULA) score was used to quantitatively assess musculoskeletal loadings and ergonomic risk [13]. A VR simulation was to replicate a preceding real-life experiment, and the participants' motions were recorded using a wearable motion capture system. These allowed us to compute body section scores, including the upper arm, lower arm, neck, and trunk, which were also analyzed to gain deeper insight into the findings.

Methodology
Data Collection
In Ontario, Canada, the 3-year masonry apprenticeship program consists of on-site and in-school training, allowing apprentices to apply for journeyman certification upon completion. This study used a subset of data from previous research that included motion data of block lifting from 66 healthy masons with varying levels of work experience, collected at the Ontario Masonry Training Centre in Waterloo and the Canada Masonry Design Centre (CMDC) in Mississauga, Ontario [14]. Specifically, this study uses and analyzes the motion data from one group of participants for completing the second and sixth courses of the pre-built wall using both hands to handle the masonry unit. To facilitate comparison, a VR simulation was developed in the Unity game engine to replicate the real-life experiment conducted previously. In the real-world experiment, all participants were male. In the VR simulation, the majority of participants were male, with two female participants included. The motion data were recorded as participants wore the motion capture suit during the VR simulation. Each participant was instructed to complete the second course and the sixth course of a pre-built wall in VR using 18 Concrete Masonry Units (CMUs) in total.

Fig. 1 illustrates the two scenarios developed in the VR simulation. The pre-built wall, shown in a lighter grey shade, consists of six courses, while the CMUs highlighted in a darker grey shade indicate the sections to be completed by the participants. In the previous real-life experiment, 16.6 kg CMUs with dimensions of 0.19 × 0.19 × 0.39 m were organized in three piles approximately one metre from the pre-built wall. Participants retrieved the CMUs individually, applied mortar and placed them in the designated locations in the wall. In the VR simulation, the setup, including the wall configuration and the dimension of each CMU, was identical to that in the real-life experiment. The key distinction was that participants lifted virtual CMUs without any weight in the VR simulation and laid them without spreading mortar. The scope of both experiments is limited to analyzing the motion behaviour of participants while lifting blocks, with no consideration of other activities such as mixing or spreading mortar. Reflecting this, the VR simulation involved only block lifting and placement, and the motion analysis of associated activity was conducted.



(a)



(b)

Figure 1: Configuration of the Pre-built Wall: (a) Second Course Scenario; and (b) Sixth Course Scenario

Both experiments captured motion data for the entire body. The previous real-life experiment used two wireless motion capturing systems, MVN Awinda and Perception Neuron [15], whereas the VR simulation experiment utilized Perception Neuron 3 (PN3), an upgraded version of the latter.[16]. This system supports unobtrusive motion capture, minimizing distraction and interference with the participants' tasks. The PN3 system uses 17 inertial sensors integrated with gyroscope, accelerometer and magnetometer [17]. The use of inertial sensors for motion capture has been proven suitable for various upper body motion analysis applications, aligning with the performance of standard optoelectronic systems [18, 19]. Figure 2 is a figure from the official website of Perception Neuron [17] that illustrates the placement of PN3 sensors across the body for motion capture.

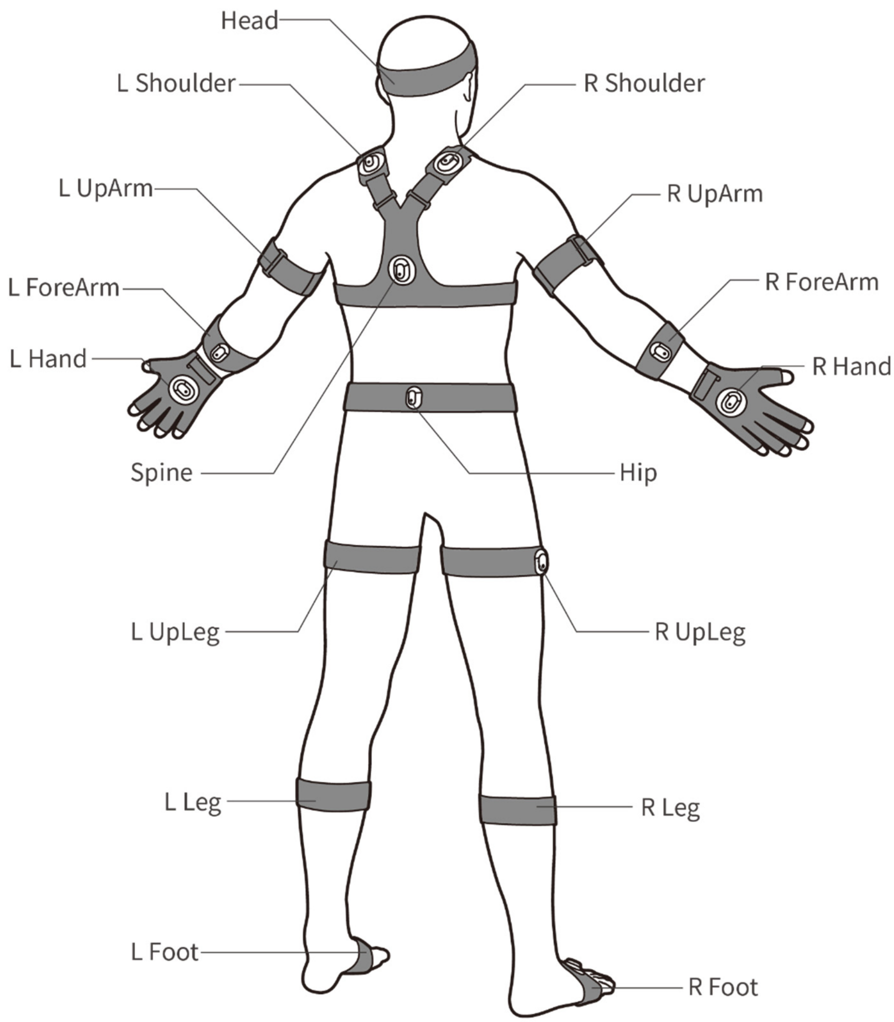
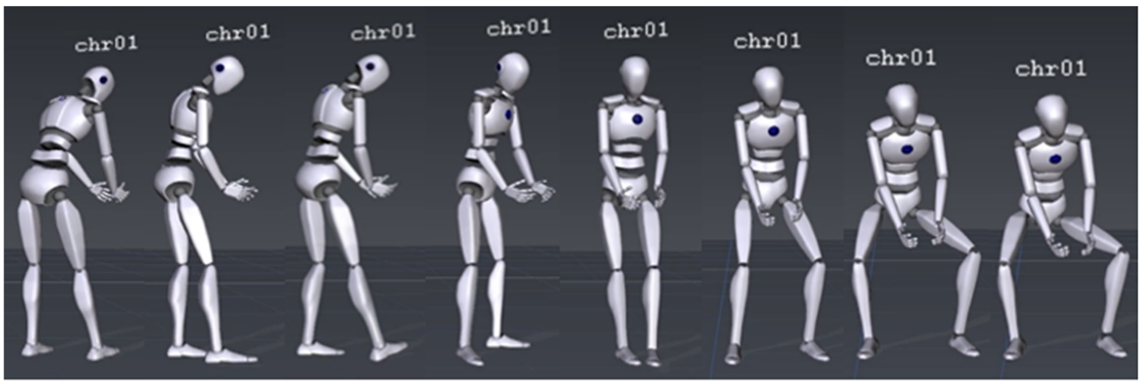


Figure 2: PN3 sensors [17]

Motion data from both experiments were recorded and subsequently exported in the BioVision Hierarchy (BVH) format using the proprietary software provided by the respective motion capture system, such as Axis Studio, which is included with PN3 by Noitom Ltd. [20]. Figure 3 illustrates a single CMU lift sequence, showcasing the process from pickup to placement from three perspectives: in real life, as a skeleton model in Axis Studio, and from a first-person view in the VR simulation.

(a)



(b)

(c)

Figure 3: A Single CMU Lift Sequence from Pickup to Placement with Perspectives Synchronized Horizontally of: (a) Participant Wearing Motion Capture Suit in Real Life; (b) Skeleton Model in Axis Studio; and (c) First-Person View in VR Simulation

Data Processing

The exported motion data from the real-life experiment (referred to as real lifts) had a frame rate of 100 frames per second (fps), while the motion data from the VR simulation experiment (referred to as VR lifts) was capped at 60 fps due to a software update. For alignment, the real lift data were down-sampled to match the frame rate of the VR lift data at 60 fps. For each frame, the 3D joint locations were extracted from the BVH files using the software BVH Viewer. Using MATLAB scripts, the data were segmented and stored in MAT-files for each lift, documenting the whole body's joint center coordinates for each frame across the complete lift motion, from CMU pickup to placement for individual lifts.

Data Analysis

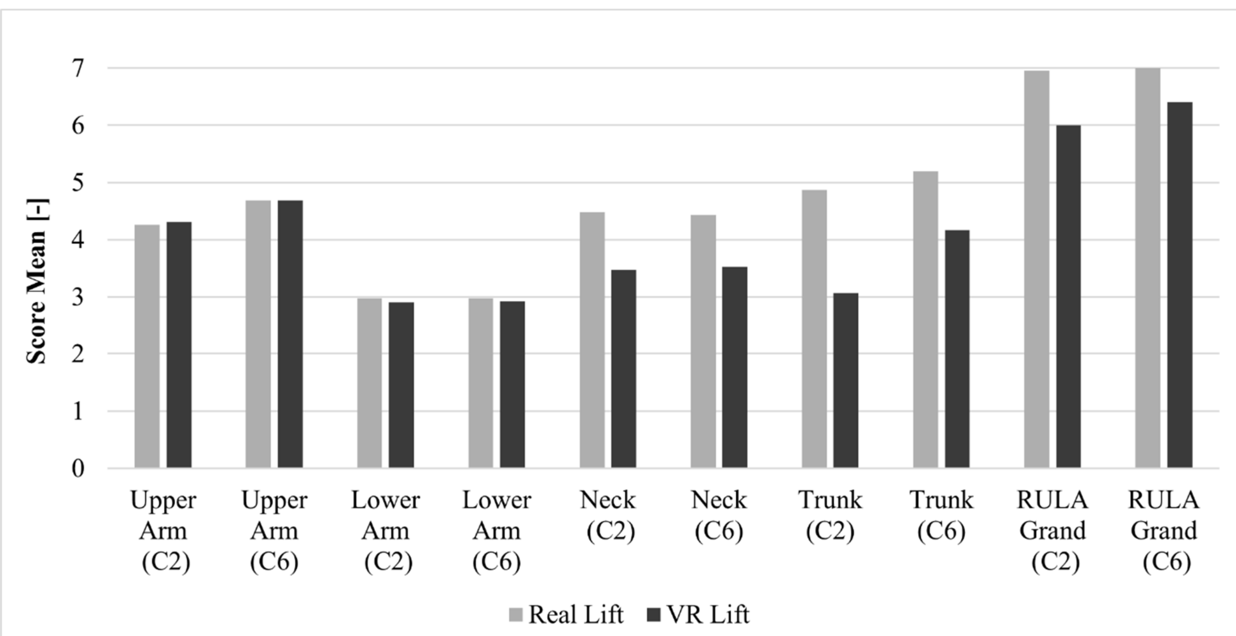
A standard and broadly used rule-based assessment system, RULA, was used to compare the human motion behaviour during real lifts and VR lifts. It is used in practice to assess risk factors linked to MSDs, specifically focusing on the upper body [21]. RULA categorizes the human body into two groups: one comprising the lower and upper arms and wrists, and the other including the neck, trunk, and legs. The RULA assessment is conducted using a standardized worksheet to calculate the final RULA grand score. For each frame, joint angles of the body are estimated from the 3D joint locations to compute body section scores. These scores are subsequently integrated through the corresponding assessment grid tables to generate two composite measures: the score of wrist and arm, and the score of neck, trunk, and leg, each incorporating adjustments for external loads and repetitive movements. These two metrics are then combined using a final assessment grid table to compute the RULA grand score [22]. As the lower back and upper limbs are the most critical body joints for MSD risks [22], the focus of this study is on the upper body.

This study compares the RULA grand score between real lifts and VR lifts, and it delves deeper into body section scores (upper arm, lower arm, neck, and trunk) to identify the primary sources of postural differences between the two lifting conditions. In accordance with the Occupational Health and Safety Council of Ontario (OHSCO) Musculoskeletal Disorders Prevention Series guidelines, instead of the cumulative effects of all movements during a lift, this study analyzed the most critical postures observed by identifying the peak score (RULA grand, upper arm, lower arm, neck and trunk scores) from all frames of each lift [23]. To ensure score comparability between real and VR lifts and to focus on motion patterns, the load penalty was excluded from the score calculation for real lifts, as the scores were highly saturated due to the external load of 16.6 kg.

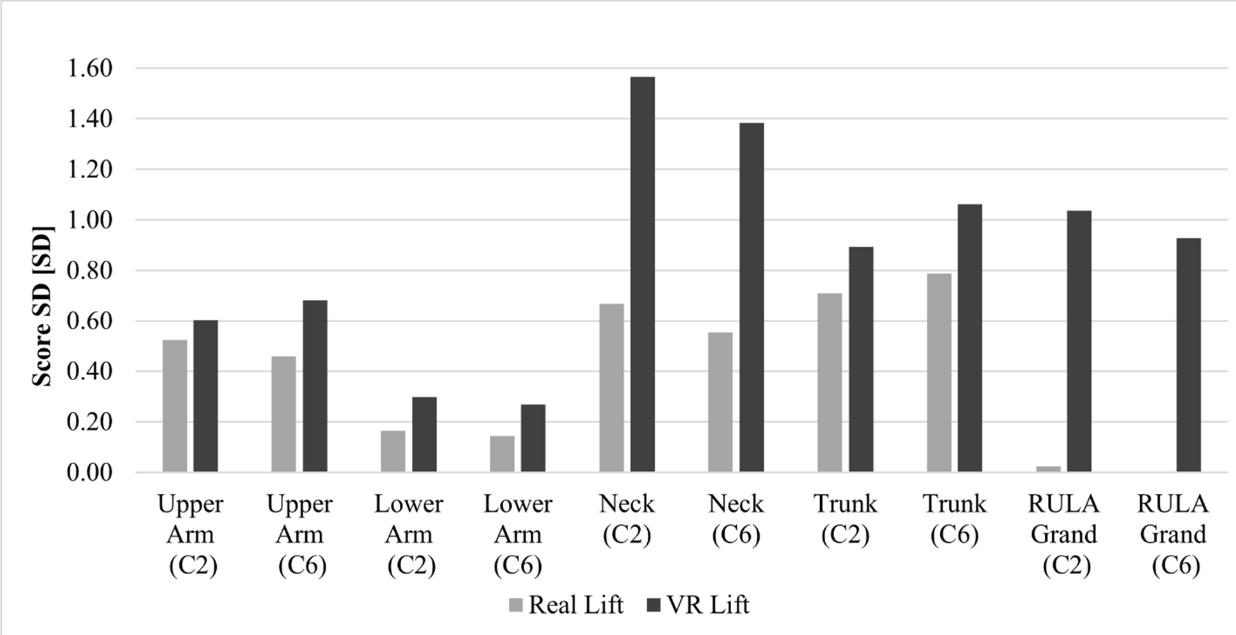
RESULTS & DISCUSSION

Descriptive Results

Figure 4 illustrates the comparison of RULA grand score and the body section scores between real and VR lifts, including their respective mean values and standard deviations (SD) for the second and the sixth course of the wall, respectively. The second and sixth courses of masonry units are named C2 and C6 respectively, which is the nomenclature used in Figure 4.



(a)



(b)

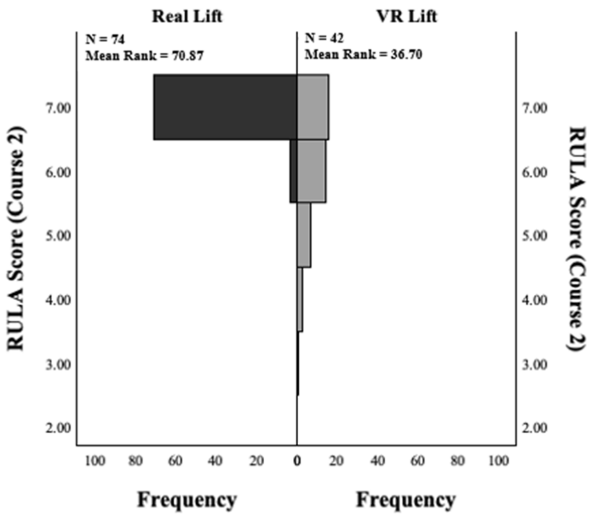
Figure 4: Comparison of RULA Grand Score and Body Section Scores Between Real and VR Lifts: (a) Mean and (b) SD (Standard Deviation)

As observed in Figure 4 (a), real lifts yield higher RULA grand scores for both courses, with the difference primarily attributed to the trunk and neck, while the upper and lower arm scores are nearly identical between real and VR lifts. Among all body sections, the most significant difference between real and VR lifts occurs in the trunk; specifically, for course 2, the mean score of real lifts exceeds that of VR lifts by approximately 1.79 (or about 60%), and for course 6, the increase is around 1.03 (or about 25%). The second most notable difference is in the neck, with the mean score of real lifts surpassing that of VR lifts by approximately 1.01 in course 2 and 0.90 in course 6. In Figure 4 (b), VR lifts show significantly higher variability in SD across the RULA grand score and all body section scores, particularly for the neck and trunk. This increased variability may stem from the less consistent and constrained movements involved in VR lifts, as the weightless virtual CMUs used in VR simulation do not replicate the 16.6 kg weight of the physical CMUs in the real-life experiment.

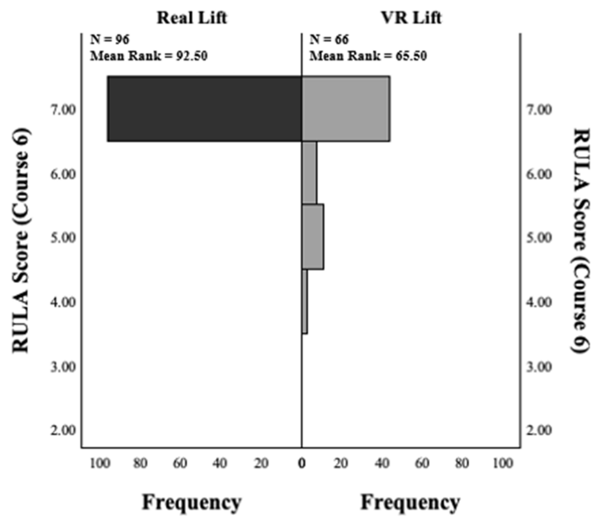
The SD remains relatively stable for real lifts between courses 2 and 6, while VR lifts show a decline of approximately 0.11 moving from course 2 to 6. Across all body sections, both real and VR lifts show a slight decrease in the SD of the neck score and a slight increase in the SD of the trunk score for course 6; however, this change is more pronounced for VR lifts. A contrasting trend is observed in the SD of the upper arm score: real lifts experience a decrease of 0.06, whereas VR lifts show an increase of 0.08 in course 6.

Statistical Analysis

To determine whether there is a statistically significant difference in human motion behaviour between real and VR lifts, the Mann-Whitney U test was performed using the software SPSS with a significance level of 5%. This non-parametric test that does not require normal distribution of data was selected in this study as the experiment data are not strictly normally distributed [24]. The observations about standard deviation in the previous section remain applicable. Given that each sample size exceeds 30, the standard deviation remains a reliable measure of variability, even if the data distribution does not strictly follow normality. Figure 5 shows the distributions of RULA grand scores for courses 2 and 6, respectively. Both courses indicate that the distributions of RULA grand scores for real and VR lifts are very different: the RULA grand scores for real lifts are mostly concentrated around 7, while the RULA grand scores for VR lifts have a broader distribution, with a considerable proportion of scores around 5 and 6.



(a)



(b)

Figure 5: Distribution of RULA Grand Scores: (a) Course 2; and (b) Course 6

Tables 1 and 2 show the results of the Mann-Whitney U test for courses 2 and 6, respectively, listing the score, lift category, sample size, mean rank, sum of ranks, u-value and p-value. The null hypothesis of this test is that the distribution of the scores is the same for VR lifts and real lifts. At a significance level of 5%, a p-value below 0.05 leads to the rejection of the null hypothesis, while a p-value exceeding 0.05 results in retaining the null hypothesis. The p-value of RULA grand scores for both courses is smaller than 0.001, which confirms that, for both courses, there is a statistically significant difference in RULA grand score between VR lifts and real lifts. The test results for the body section scores further indicate that the difference is primarily driven by the trunk and neck scores, whereas the upper arm and lower arm scores show similarity: for both courses, neck and trunk scores have a p-value smaller than 0.001, leading to the rejection of the null hypothesis; in contrast, upper arm and lower arm scores have a p-value greater than 0.05 retaining the null hypothesis.

Table 1: Mann-Whitney U Test Results (Course 2)

Score	Lift Category	N	Mean Rank	Sum of Ranks	U	P
RULA Grand	Real Lift	74	70.87	5244.38	2469.50	< 0.001
	VR Lift	42	36.70	1541.4		
Upper Arm	Real Lift	74	57.64	4265.36	1490.50	0.664
	VR Lift	42	60.01	2520.42		
Lower Arm	Real Lift	74	59.93	4434.82	1660.00	0.112
	VR Lift	42	55.98	2351.16		
Neck	Real Lift	74	65.96	4881.04	2106.00	< 0.001
	VR Lift	42	45.36	1905.12		
Trunk	Real Lift	74	76.49	5660.26	2885.00	< 0.001
	VR Lift	42	26.81	1126.02		

Table 2: Mann-Whitney U Test Results (Course 6)

Score	Lift Category	N	Mean Rank	Sum of Ranks	U	P
RULA Grand	Real Lift	66	92.50	6105.00	4224.00	< 0.001
	VR Lift	96	65.50	6288.00		
Upper Arm	Real Lift	66	82.54	5447.64	3268.00	0.694
	VR Lift	96	79.98	7678.08		
Lower Arm	Real Lift	66	83.31	5498.46	3342.00	0.092
	VR Lift	96	78.86	7570.56		
Neck	Real Lift	66	93.76	6188.16	4345.00	< 0.001
	VR Lift	96	63.67	6112.32		
Trunk	Real Lift	66	99.06	6537.96	4854.00	< 0.001
	VR Lift	96	55.95	5371.20		

CONCLUSION & RECOMMENDATIONS

This study examined the use of VR for ergonomics training in masonry work by comparing human motion behaviour during block lifting in real and VR environments. A VR simulation was developed to replicate the previous real-life experiment with the same scenario and setup. The key findings reveal a significant difference in motion behaviour between real and VR lifts, primarily due to the limitation of VR simulation to include the physical weight involved in real-life masonry work. As a result, real lifts yielded higher RULA grand scores than VR lifts, with the higher scores being attributed to the trunk and neck. This suggests that while VR offers valuable safety training opportunities, it cannot simulate the physical demands of masonry tasks, limiting its effectiveness for ergonomics training. Based on these findings, the use of VR for masonry ergonomics training is not recommended. Future research should focus on exploring alternative methods that can more accurately simulate the physical weight of blocks and add haptic feedback to improve training outcomes in VR.

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